# Evidence that a Deep Meridional Flow Sets the Sunspot Cycle Period

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## ABSTRACT

Sunspots appear on the Sun in two bands on either side of the equator that drift toward lower latitudes as each sunspot cycle progresses. We examine the equatorward drift of the centroid of the sunspot area in each hemisphere from 1874 to 2002 and find that the drift rate slows as the centroid approaches the equator. We compare the drift rate at sunspot cycle maximum to the cycle-period for each hemisphere and find a highly significant anti-correlation: hemispheres with faster drift rates have shorter periods. These observations are consistent with an equatorward meridional counterflow, deep within the Sun, as the primary driver of the equatorward migration and the period associated with the sunspot cycle. We also find that the drift rate at maximum is significantly correlated with the amplitude of the following cycle, a prediction of dynamo models that employ a deep equatorward meridional flow. Our results indicate an amplitude of about 1.2 m/s for the meridional flow velocity at the base of the solar convection zone.

*Subject headings:* Sun: activity — Sun: magnetic fields — Sun: interior

## 1. Introduction

Understanding the nature of the Sun's magnetic cycle remains one of the most challenging areas of solar astronomy. Similar cycles are also found on other stars (Wilson 1978; Baliunas et al. 1995). Scientific inquiry into the nature of the sunspot cycle is more than an academic exercise. Most of our technology in space and some technologies on the surface of our planet are at risk due to solar activity that waxes and wanes with the sunspot cycle. Terrestrial climate may also be influenced by solar activity to an extent that may confuse the nature and significance of anthropogenic forcing on climatic change (Kerr 1995; Wilson 1998).

Solar magnetic activity is most strikingly portrayed in the form of sunspots - regions of concentrated magnetic fields observed on the surface of the Sun. The sunspot cycle itself has two main discernable components: the 11-year periodic variation in the number and polarity of sunspots seen on the solar surface (Schwabe 1844; Hale et al. 1919) and the equatorward migration of the sunspot formation belt (Carrington 1858). At the very least, a successful model of the solar magnetic cycle should reproduce these two key features. Recent progress in solar magnetic dynamo modeling has suggested that an equatorward meridional flow, deep within the Sun, plays important, but previously unrecognized roles in driving the sunspot cycle (van Ballegooijen & Choudhuri 1988; Wang, Sheeley & Nash 1991; Choudhuri, Schüssler & Dikpati 1995; Durney 1995, 1997; Dikpati & Charbonneau 1999; Dikpati & Gilman 2001; Nandy & Choudhuri 2001, 2002; Wang, Lean & Sheeley 2002). In this study we find strong evidence supporting those models.

Models of the solar dynamo have established that the solar cycle involves a re-cycling of the two main components of the Sun's magnetic field (Parker 1955). The toroidal component of the magnetic field is generated by the shearing of the poloidal field in a region of strong radial gradient in the rotation known as the tachocline - located at the base of the solar convection zone (SCZ). Sufficiently strong toroidal flux tubes become buoyant and rise to the solar surface forming sunspots. It was believed that equatorward propagation of this toroidal field wave at the base of the SCZ manifested itself on the surface as the equatorward migration of the sunspot activity belt. The poloidal component of the magnetic field (identified with the weak, diffuse field observed outside of sunspots) is re-generated from the toroidal field by a process known as the alpha-effect in which the toroidal field is lifted and twisted into the meridional plane. Contrasting mechanisms (e.g., helical convection (Parker 1955); decay of tilted bipolar sunspot pairs (Babcock 1961); buoyancy instability coupled with rotation (Brandenburg & Schmitt 1998); hydrodynamic instability of the differential rotation (Dikpati & Gilman 2001)) have been proposed to explain the origin of this alpha-effect. Though these various mechanisms differ in their nature and location, one common feature is that all of them predict a positive alpha-effect in the northern hemisphere of the Sun and a negative alpha-effect in the southern hemisphere.

In recent years, with the advent of helioseismology, it became possible to map out the rotation in the solar interior (Rhodes et al. 1990; Thompson et al. 1996) and it was discovered that the radial gradient in the rotation ($\partial\Omega/\partial r$) in the low-latitude tachocline is also positive. If the product of the sign of alpha-effect and the radial rotational gradient $\partial\Omega/\partial r$ is positive in the northern hemisphere of the Sun, then the toroidal magnetic wave generated by the solar dynamo would propagate poleward (Yoshimura 1975), in contrast to the observations of equatorward migration of the sunspot formation belt. This led to a well-known dilemma in solar dynamo theory regarding the direction of propagation of the dynamo wave (Parker 1987). Subsequently, it was demonstrated that a meridional flow that is directed equatorward at the base of the SCZ could carry the dynamo wave towards the equator, thus resolving the dilemma (Choudhuri, Schüssler & Dikpati 1995; Durney 1995). It is important to realize here that the equatorward migration of sunspot activity belt that we see, is then a direct consequence of the almost passive (conveyor belt type) transport of the toroidal magnetic field by the meridional circulation and not a "simple" dynamo wave – which would propagate towards the pole if such an equatorward meridional flow were lacking (Choudhuri, Schüssler & Dikpati 1995; Nandy & Choudhuri 2001).

In spite of theoretical predictions of the alpha effect being positive in the northern hemisphere, some modelers working without a meridional flow, prescribe a negative alpha-effect in order to get the correct migratory behavior of the dynamo wave at low latitudes (Rüdiger & Brandenburg 1995). However such models produce butterfly diagrams with two branches (due to the different signs of $\partial\Omega/\partial r$ in the high and low latitude tachocline): a low latitude branch that propagates towards the equator and a high latitude branch (of comparable strength) that propagates towards the pole, characterized by nearly constant drift velocities in each branch (Rüdiger & Brandenburg 1995). This kind of branching in the butterfly diagram, however, has not been observed.

A poleward meridional flow is observed in the outer half of the SCZ (Hathaway 1996; Braun & Fan 1998) and has been used earlier to model the evolution of the weak, diffuse poloidal field on the surface (Wang, Sheeley & Nash 1991; Dikpati & Choudhuri 1994). Fluctuations in the meridional flow (Hathaway 1996) - believed to be a product of turbulent convection – have also successfully accounted for variations in the solar cycle that are superposed on the otherwise stable 11-year periodicity (Charbonneau & Dikpati 2000; Wang, Lean & Sheeley 2002). From this it has been conjectured that the meridional circulation acts like a "solar-clock" setting the cycle period. The predicted deep equatorward counter-flow may also have a role in confining the sunspot formation belt to low latitudes (Nandy &

Choudhuri 2002). However, this equatorward counterflow, presumably located somewhere near the base of the SCZ, has eluded observational detection.

## 2. Observations, Analyses and Results

We look for evidence that a deep meridional flow indeed carries the toroidal field equatorward and controls the period of the sunspot cycle, by examining the latitudinal drift of the sunspot bands in each hemisphere. The Royal Greenwich Observatory (RGO) compiled sunspot observations from a small network of observatories to produce a dataset of daily observations on the positions and sizes of sunspot groups starting in May 1874. The observatory concluded this dataset in 1976 after the US Air Force (USAF) started compiling data from its own Solar Observing Optical Network. This work was continued with the help of the US National Oceanic and Atmospheric Administration (NOAA) with much of the same information being compiled in their daily Solar Region Summaries through to the present. We have reformatted the USAF/NOAA data to conform to the RGO data and calibrated the sunspot area measurements using sunspot area data from the Mount Wilson Observatory (Howard, Gilman & Gilman 1984). The Mount Wilson data cover the years 1921 to 1982 and thus span the transition between the RGO and USAF/NOAA datasets. We use these daily records for the positions and areas of sunspot groups from 1874 to 2002 to determine the daily sunspot area in equal-area latitude strips averaged over individual 27.275-day solar rotations. Plotting the sunspot group positions versus time gives the familiar "Butterfly Diagram" (Fig. 1) which shows how the bands of sunspots drift toward the equator and how successive cycles overlap at the time of sunspot cycle minimum.

We find the positions of the sunspot bands by first separating the individual cycles. Magnetic polarity observations can be used to determine the cycle associations of sunspot groups during the last three sunspot cycle minima (since the magnetic polarity of the sunspot groups reverses from one cycle to the next). We find that these and the remaining cycles can be easily separated using diagonal lines that pass between adjacent cycles. For simplicity we use the same slopes for all of these lines and a common intercept with the equator for each hemisphere. These diagonal lines are plotted in Fig. 1. We then find the centroid position (latitude) for the sunspot area in both the northern and southern hemispheres for each solar rotation during sunspot cycles 12 through 23. These centroid positions are fit with second-order polynomials in time relative to the time of cycle maximum as given by the smoothed total sunspot area. All 24 hemisphere/cycles show equatorward drift with an average velocity at the time of maximum of $2.0 \pm 0.2$ °/yr or $0.8 \pm 0.08$ m/s at the surface. All but one of the hemisphere/cycles (northern hemisphere of cycle 21) show a slowing of the drift velocity as the bands approach the equator. None of the hemisphere/cycles show evidence for a poleward migrating branch. Combining all 24 hemisphere/cycles shows the same result (Fig. 2). The sunspot bands start at about 25°, move equatorward to reach 15° some 4 years later at cycle maximum, and then slow to a halt at about 8° at the end of the cycle. This slowing of the drift rate at lower latitudes was noted when butterfly diagrams were first plotted (Maunder 1904) and was recently quantified in a similar study (Li, Yun & Gu 2001).

We use the polynomial fits to the centroid positions to determine the drift velocity as functions of latitude for each of the hemisphere/cycles (Fig. 3). This also shows (with few exceptions) that the equatorward drift velocity slows to a halt at about 8°. This change in drift velocity with latitude is precisely what is expected from a deep meridional flow. As the converging flows from the opposite hemispheres approach the equator they should slow and turn toward the surface (in an up-flow) where the rapid (20 m/s) poleward return flow is measured. The toroidal field belt being carried by the meridional flow will also slow down with the latter and this will result in a slowing of the sunspot drift velocity. Such up-flow cells in the circulation will effectively stop the horizontal (equatorward) migration of the toroidal field belt on either side of the equator.

The speed of the deep equatorward counterflow, which is an important parameter in models of the solar dynamo, has remained observationally unconstrained. An examination of Fig. 3 shows that the equatorward drift velocity is highest at the higher latitudes. At 25° the average velocity is 1.2 m/s (but quite variable from cycle-to-cycle). Since the velocities continue to increase at higher latitudes and might be expected to follow a simple sinusoid with a peak at 45° latitude, this should be a lower limit for the average peak velocity. This translates to a speed of 0.9 m/s at the base of the SCZ (0.7R; where R is the solar radius) at the same 25° latitude. Assuming a sinusoidal behavior with an additional 33% increase in flow velocity at the peak gives an amplitude of about 1.2 m/s for the average equatorward counterflow at the base of the SCZ. Variations in this flow speed from cycle-to-cycle should be quite large as judged by the variations seen at 25° in Fig 3. – a result consistent with the dynamo modelling of Charbonneau & Dikpati (2000) and Wang, Lean & Sheeley (2002).

We examine the correlation between the drift velocity at cycle maximum and the length of the cycle measured from minimum to minimum in smoothed sunspot area for each hemisphere. Although there is considerable scatter in the measurements we find a highly significant (95% confidence level) anti-correlation (cross-correlation coefficient -0.5) between these two quantities (Fig. 4). Cycles with faster drift rates (at cycle maximum) have shorter periods. Such an inverse dependence of the cycle period on the flow speed is a fundamental aspect of flux-transport dynamo models employing meridional circulation to transport magnetic flux across latitudes (Choudhuri, Schüssler & Dikpati 1995; Durney 1995, 1997; Dikpati & Charbonneau 1999; Dikpati & Gilman 2001; Nandy & Choudhuri 2001, 2002; Wang, Lean & Sheeley 2002).

Finally, we study the relationship between the drift velocities and the amplitudes of the hemisphere/cycles. In Fig. 5 we compare the drift velocity at the maximum of the cycle to the amplitude of that cycle for that hemisphere. There is a positive (0.5) and significant (95%) correlation between the two. However, an even stronger relationship is found between the drift velocity and the amplitude of the *following* cycle. The correlation is stronger (0.6) and more significant (99%) as shown in Fig. 6. This relationship is suggestive of a "memory" in the solar cycle, again a property of dynamo models that use meridional circulation. This behavior is, however, more difficult to interpret and we elaborate on this in the next section. In either case these correlations only explain part of the variance in cycle amplitude (25% for the current cycle and 36% for the following cycle). Obviously, other mechanisms such as variations in the gradient in the rotation rate also contribute to the cycle amplitude variations. Our investigation of a possible connection between drift rate and the amplitude of the second following cycle gives no significant correlation at this longer, two-cycle, time-lag.

## 3. Discussion

We have analyzed butterfly diagrams for the latitudinal migration of sunspots with time over a period of 128 years. Under the assumption (albeit well accepted and probably right) that the sunspot butterfly diagram reflects the distribution and evolution of the dynamo generated toroidal field belt at the bottom of the SCZ (that buoyantly rises to form sunspots), our results support the existence of a deep equatorward counterflow somewhere near the base of the SCZ. The results show that the equatorward drift slows as the sunspot bands approach low latitudes. A meridional counterflow, carrying the toroidal field belt toward low latitudes in both the hemispheres, would converge near the equator and result in a vertical up-flow (and loss of horizontal momentum), thus stopping the latitudinal drift of the toroidal field belt (and hence sunspots). The observed halt at 8° can be attributed in part to the effects of the Sun's rotation on the motions of the rising magnetic loops. As the magnetic loops that form sunspots rise from the base of the SCZ they tend to move toward the rotation axis and break through the surface (forming sunspots) at higher latitudes than their original latitudes at the base of the SCZ (Choudhuri & Gilman 1987; Fan, Fisher & DeLuca 1993).

There is no evidence for a poleward moving branch at higher latitudes. That, coupled with the fact that the sunspot drift rate slows down at low latitudes, seems to rule out dynamo models that employ a simple dynamo wave propagation as the source of sunspot drift. These dynamos, on the contrary, predict nearly constant drift velocities as is evidenced from the tilt of the simulated butterfly diagrams (Rüdiger & Brandenburg 1995; Moss & Brook 2000).

The anti-correlation we find between the period of the cycle and the drift rate of the sunspot latitude bands also strongly supports dynamo models in which the meridional flow sets the cycle period. All of these models produce a similar relationship between the meridional flow speed and the cycle period. From our results, we have estimated that the amplitude of the deep equatorward counterflow is about 1.2 m/s (attained at mid-latitudes at the base of the SCZ) and is highly variable.

While we find a significant correlation between the drift rate and the amplitude of a cycle, the stronger and more significant correlation is between the drift rate and the amplitude of the *following* cycle. A similar relationship has been found between cycle periods and cycle amplitudes as seen in the longer record of sunspot numbers (Hathaway, Wilson & Reichmann 1999, 2002; Solanki et al. 2002). Wang, Lean & Sheeley (2002) recently found that variations in the (surface) meridional flow are *needed* in their flux transport models to maintain stable magnetic polarity oscillations. (Although in their simulations the noted correlation is between current cycle surface flow speed and cycle amplitude.) Our results suggest that the solar cycle has a time delay or memory mechanism due to which information (physical characteristics) manifests (survives) after a one-cycle time lag. Stochastic fluctuations in the parameters determining the solar magnetic cycle (due to the inherent turbulent nature of the dynamo mechanism and the large scale flows) can lead to cycle amplitude and period modulation (Choudhuri 1992; Ossendrijver & Hoyng 1996; Charbonneau & Dikpati 2000; Wang, Lean & Sheeley 2002). If the system has memory, then the signatures of these amplitude and period modulations may survive and show up after a certain time lag. Such a time delay mechanism is built into flux transport dynamo models, since a finite time (of the order of the cycle period) is required for the meridional flow to bring down the surface poloidal field to the low-latitude tachocline where the toroidal field of the next cycle is generated. These models, can in turn, successfully account for much of the observed cycle amplitude and period modulations (Durney 2000; Charbonneau & Dikpati 2000; Charbonneau 2001; Wang, Lean & Sheeley 2002).

To conclude, we have reported here strong observational evidence that a deep equatorward meridional flow is driving the sunspot cycle. This flow sets the cycle period and influences the amplitude of the current and, more importantly, the following cycle. These results are strongly suggestive about the role of the meridional circulation as a “timekeeper” or a solar-clock for the solar cycle. The Sun’s radiative output varies with the number of sunspots on the solar surface, while the dipolar field is responsible for the open flux that provides pathways for magnetic storms to emanate from the Sun and affect geomagnetic space weather. Unraveling solar magnetic variability is therefore of vital importance and that may well depend on how well we understand such large scale flows in the solar interior and how they affect the Suns magnetic output.

We are indebted to the Royal Greenwich Observatory, the United States Air Force, the US National Oceanic and Atmospheric Administration, and their associated observatories for compiling the sunspot observations used in this study. D.H.H., R.M.W., and E.J.R. are supported by a grant from NASA's Sun- Earth Connection SR&T program. D.N. acknowledges financial support from NASA through SR&T grant NAG5-6110. The authors also acknowledge many helpful comments from an anonymous referee.

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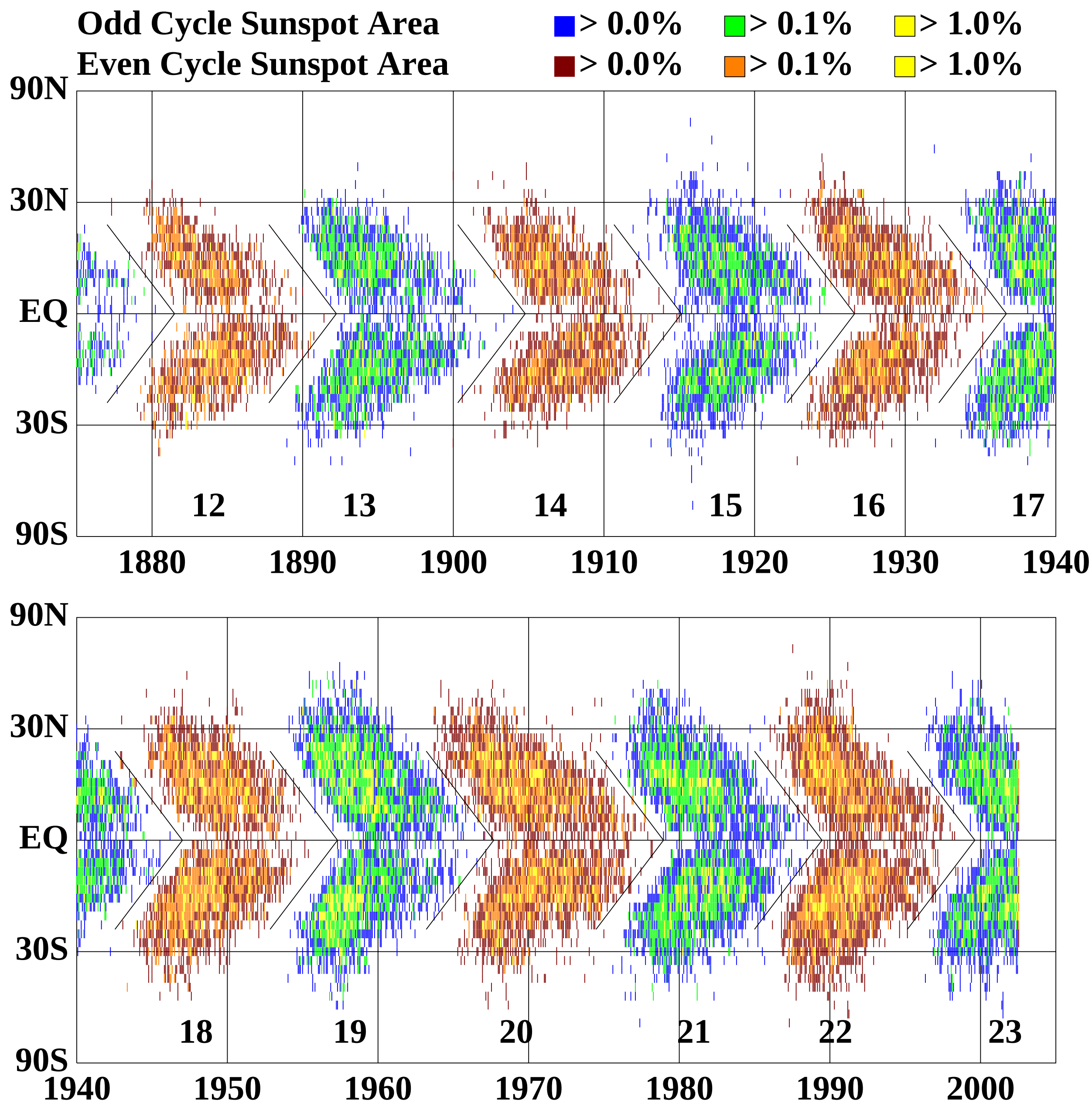


Fig. 1.— "Butterfly Diagram"showing sunspot area as a function of latitude and time. The Sun's surface is divided into 50 equal area latitude bands. The daily sunspot area in each band (averaged over 27.275 day solar rotations) is plotted on a logarithmic scale using the color key. Adjacent cycles are separated using the diagonal lines which have a common intercept with the equator for each hemisphere and slopes that are the same for each cycle. This diagram shows the familiar equatorward drift of the sunspot latitude bands, as well as the tendency to avoid the equator itself and for cycles to overlap at minimum. (Sunspot cycle numbers along the bottom of each panel are centered on the times of sunspot cycle maximum.)

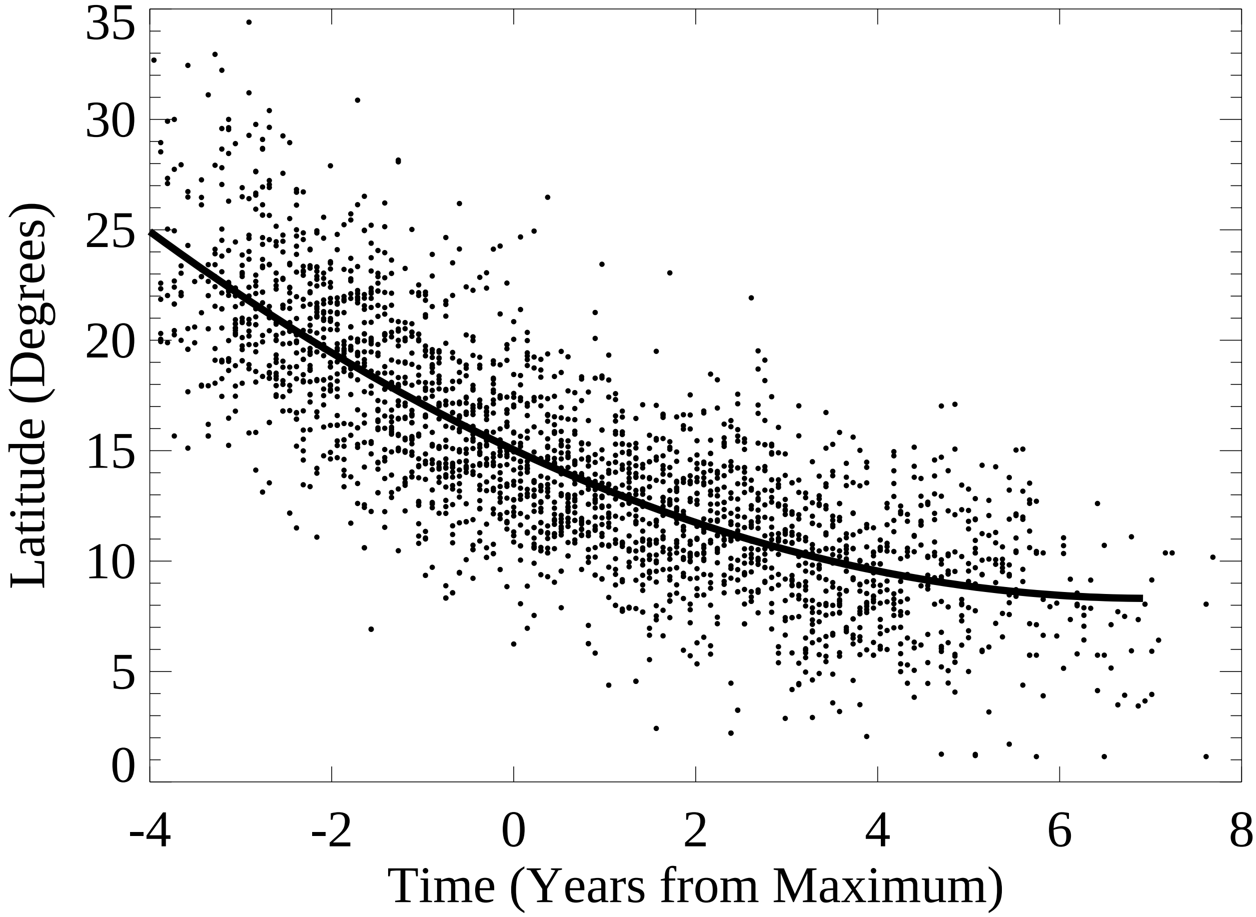


Fig. 2.— Latitude of the centroid of the sunspot area versus time relative to the time of sunspot cycle maximum. Each cycle is separated from the preceding and following cycles using the diagonal lines shown in Fig. 1. The centroid position of the sunspot area for each hemisphere and for each rotation of the Sun is plotted as an individual dot using the time measured relative to the time of maximum smoothed sunspot area for that cycle. A second order polynomial fit to these points is shown by the thick black line. The equatorward drift rate slows as the sunspot bands approach the equator and stops at about 8°. This behavior is expected if a deep meridional flow is responsible for the equatorward drift.

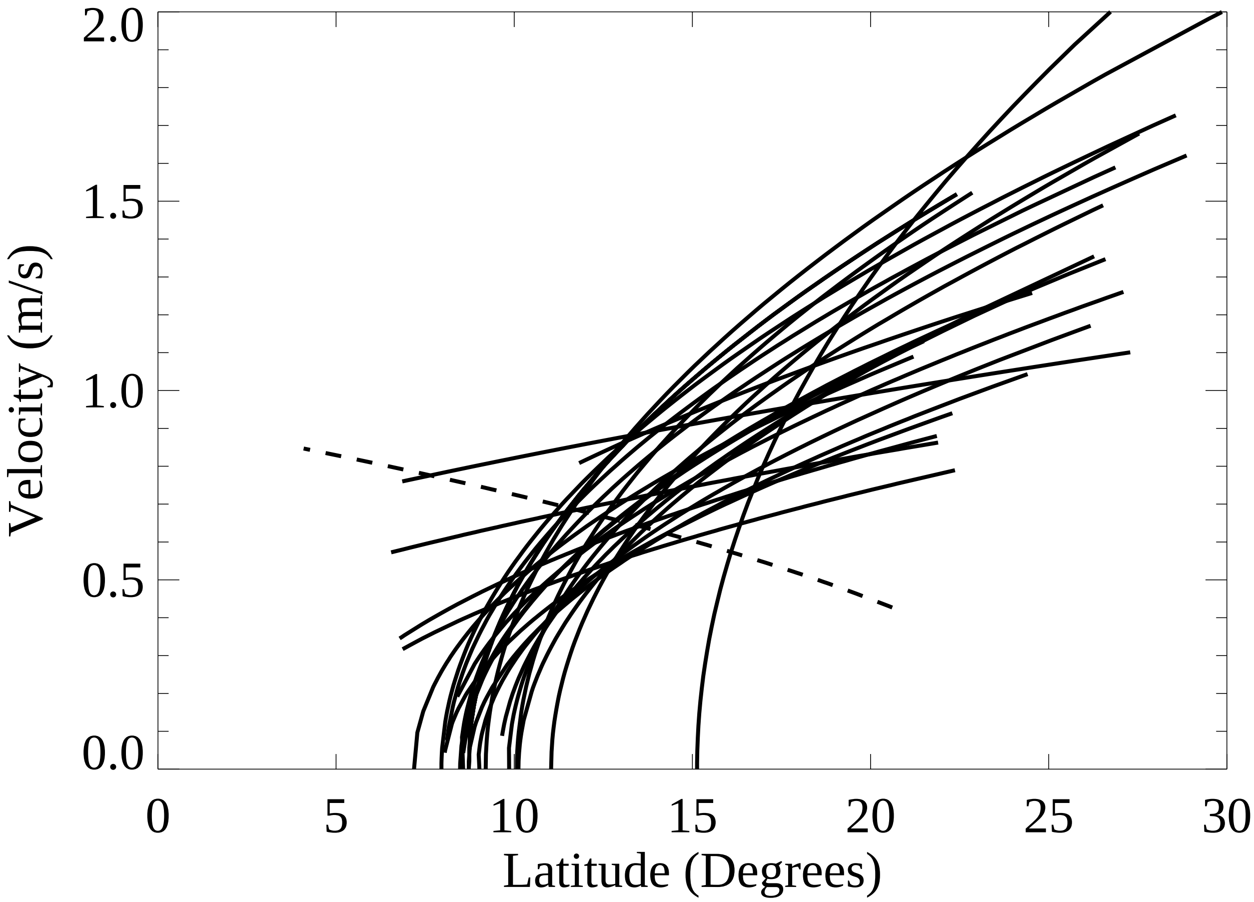


Fig. 3.— Equatorward drift velocity of the sunspot bands as functions of latitude for each hemisphere/cycle. These curves are derived from the second order polynomial fits to the sunspot area centroid positions for each hemisphere/cycle. With one exception (the northern hemisphere of cycle 21 shown by the dashed line) the drift velocities decrease with latitude as the sunspots bands approach the equator.

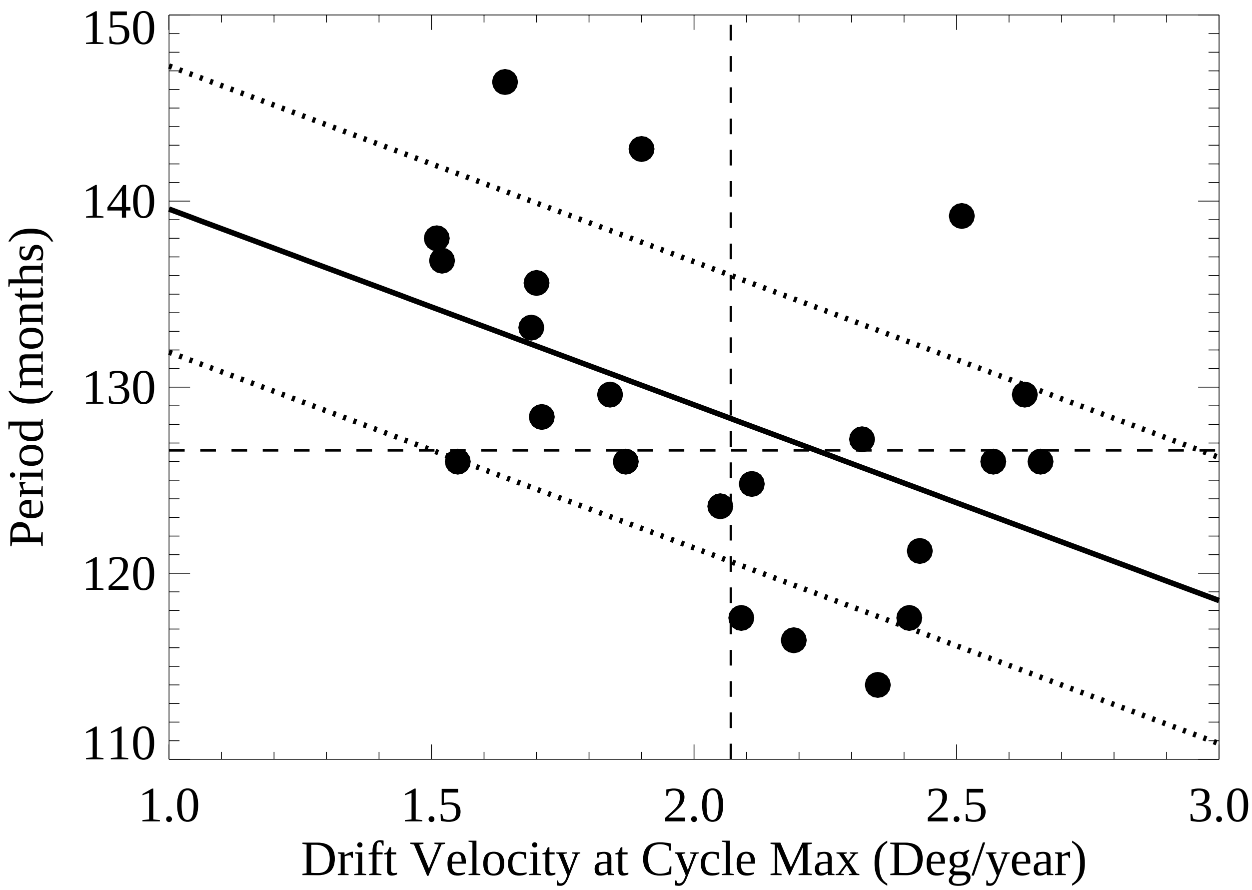


Fig. 4.— Cycle period versus equatorward drift velocity at sunspot maximum for each hemisphere/cycle. The cycle periods are anti-correlated with the drift velocities. The solid line shows the best linear fit through the points while the dotted lines show the 1-sigma limits. The dashed lines give the median values of the two plotted quantities. The probability of getting this distribution, or one even more suggestive of a departure from independence, from two independent quantities is less then 5%. Hemisphere/cycles with fast drift rates have short periods. This relationship is characteristic of dynamo models that employ a deep meridional flow to transport magnetic flux toward the equator.

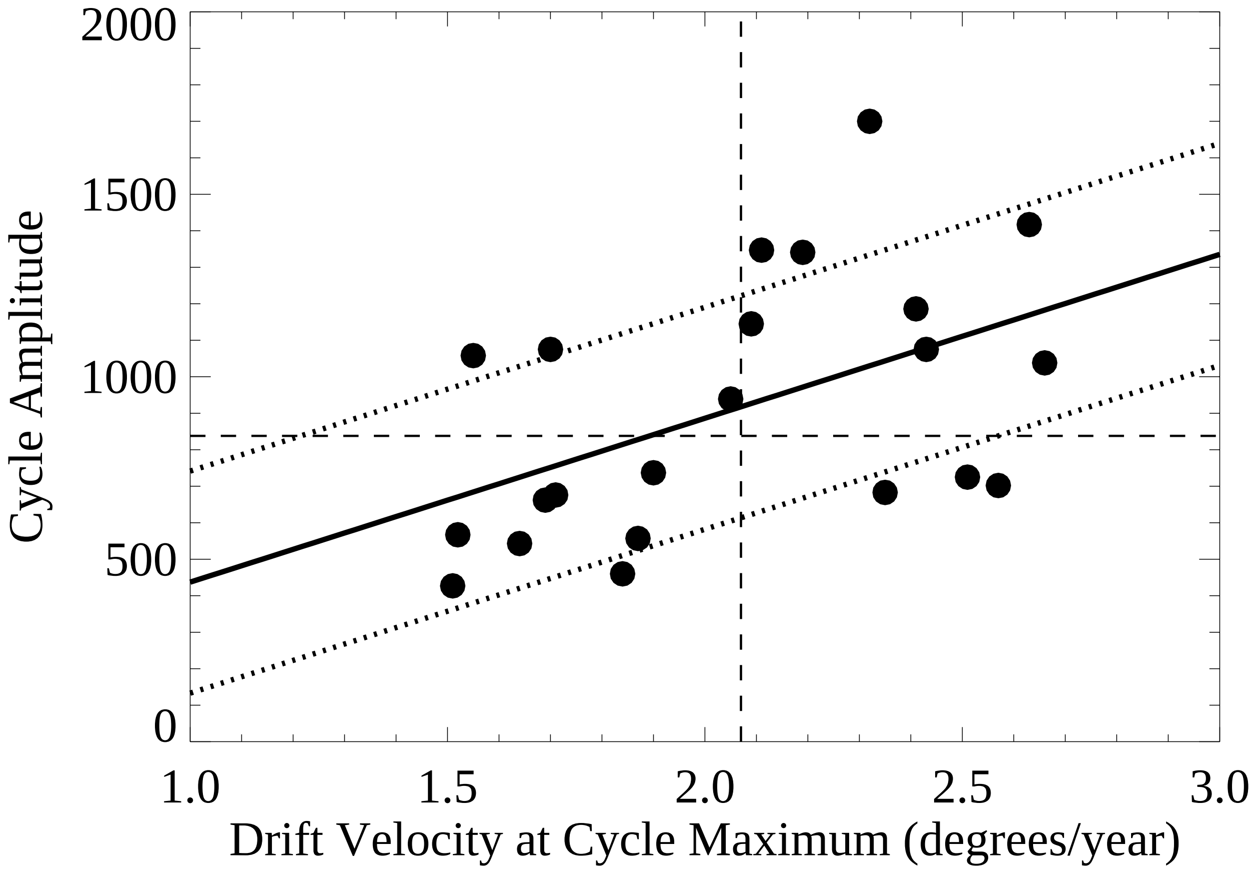


Fig. 5.— Cycle amplitude (sunspot area in millionths of a hemisphere) versus equatorward drift velocity at sunspot maximum for each hemisphere/cycle. The cycle amplitudes are correlated with the drift velocities. The solid line shows the best linear fit through the points while the dotted lines show the 1-sigma limits. The dashed lines give the median values of the two plotted quantities. The cross-correlation coefficient is 0.5 and the chance of obtaining this distribution from uncorrelated quantities is less than 5%.

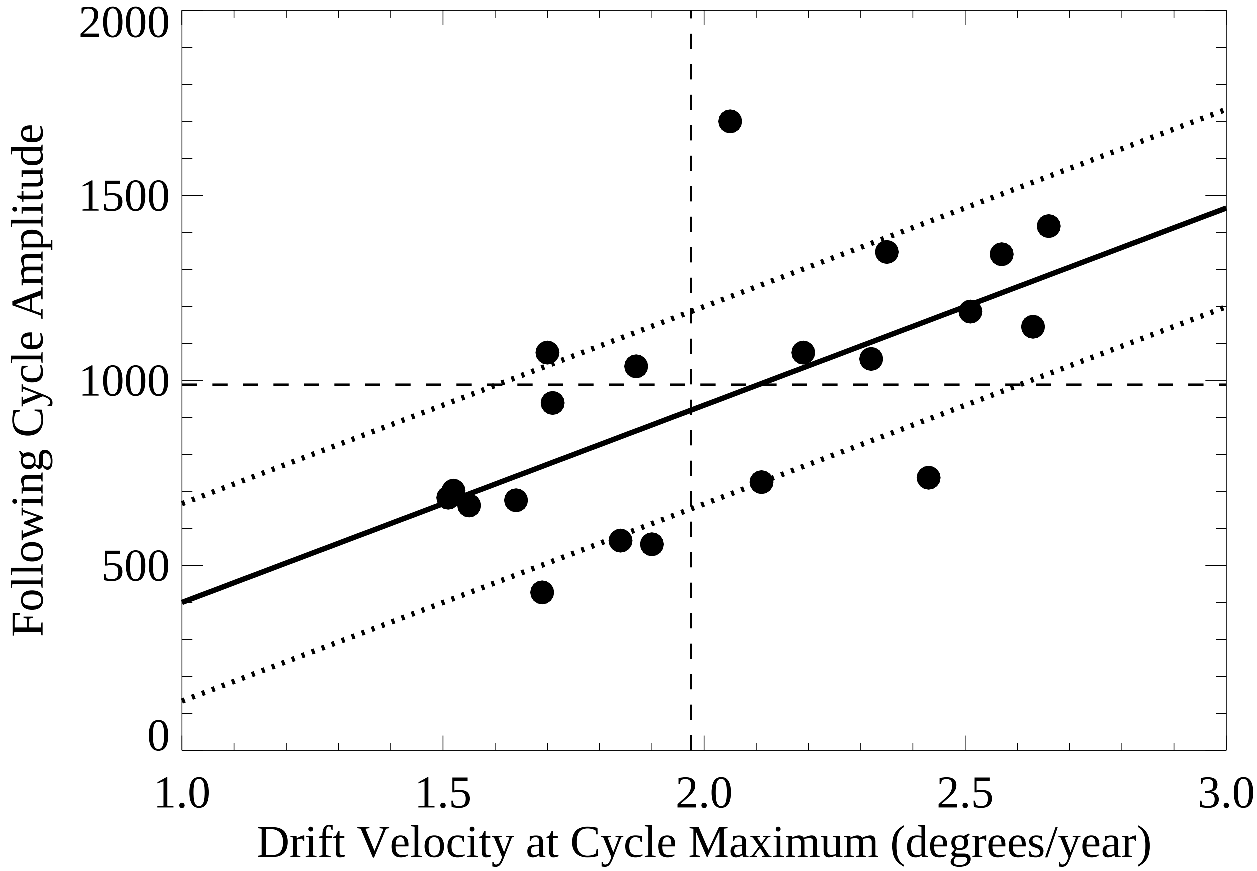


Fig. 6.— Cycle amplitude (sunspot area in millionths of a hemisphere) for the following cycle versus equatorward drift velocity at sunspot maximum for each hemisphere/cycle. The following cycle amplitudes are correlated with the drift velocities. The solid line shows the best linear fit through the points while the dotted lines show the 1-sigma limits. The dashed lines give the median values of the two plotted quantities. The cross-correlation coefficient is 0.6 and the chance of obtaining this distribution from uncorrelated quantities is less than 1%.